

# TOPICS IN ELECTROCHEMICAL DEGRADATION OF PHOTOVOLTAIC MODULES

JET PROPULSION LABORATORY

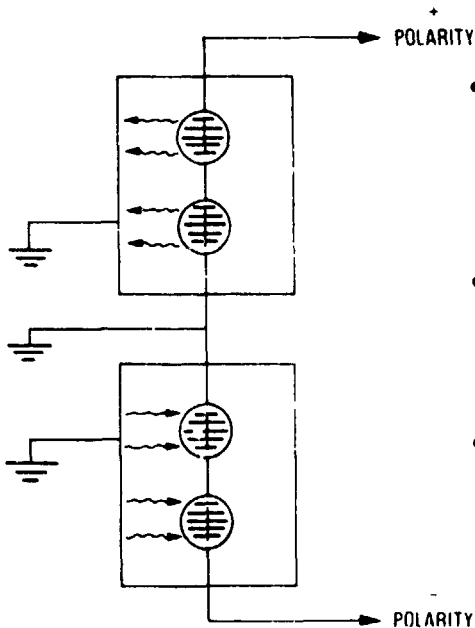
G.R. Mon

## Topics

- The relationship between leakage current and electrochemical degradation
  - Positive and negative polarity
  - Dependence on temperature and humidity
- Leakage-current response mechanisms
  - Experimental observations
    - The effect of non-metallized substrate films
    - The effect of cell-frame gap dimension
    - The effect of applied voltage magnitude
    - The effect of pollutant ion mobility
  - Physical deductions
- Laboratory-field equivalence -- acceleration factors
  - Module life prediction
  - Module (electrochemical) qualification test

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## The Relationship Between Leakage Current and Electrochemical Damage



- Cell string and frame behave as opposite-polarity electrodes; the intervening pottant behaves as a solid-state electrolyte
- Module leakage current increases with increasing temperature and relative humidity
- Observed and electrically measured electrochemical damage increases with increasing accumulated charge transfer

### Electrochemical Damage: Positive and Negative Polarity

#### ■ Positive polarity

- Metallization dissolution and migration (from cell to frame)
- Cathodic dendrite formation (from frame to cell)
- Evolution of gas at cathode (frame)

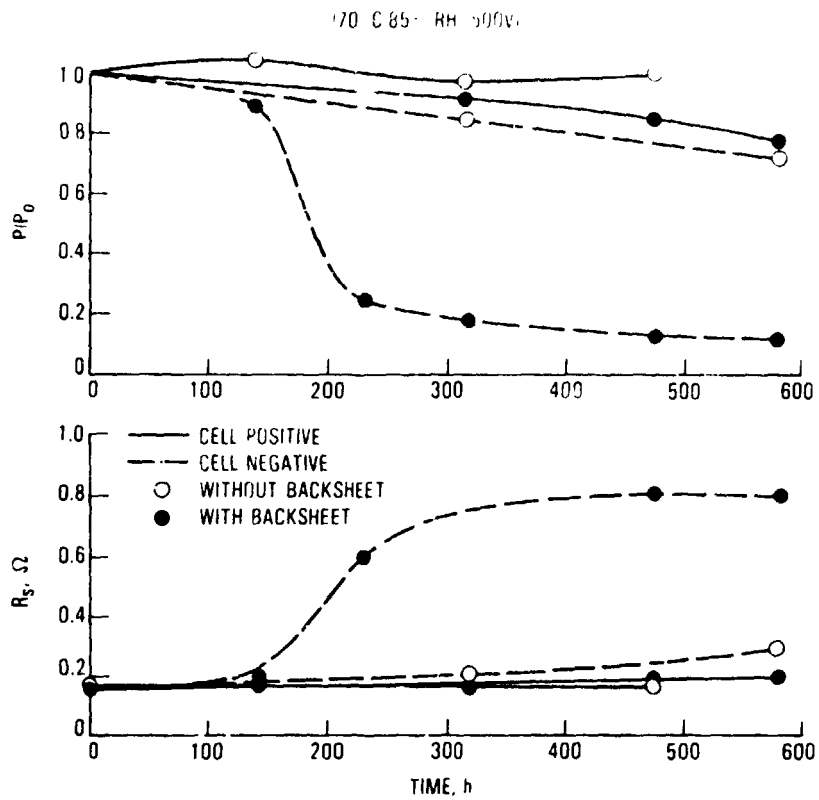
#### ■ Negative polarity

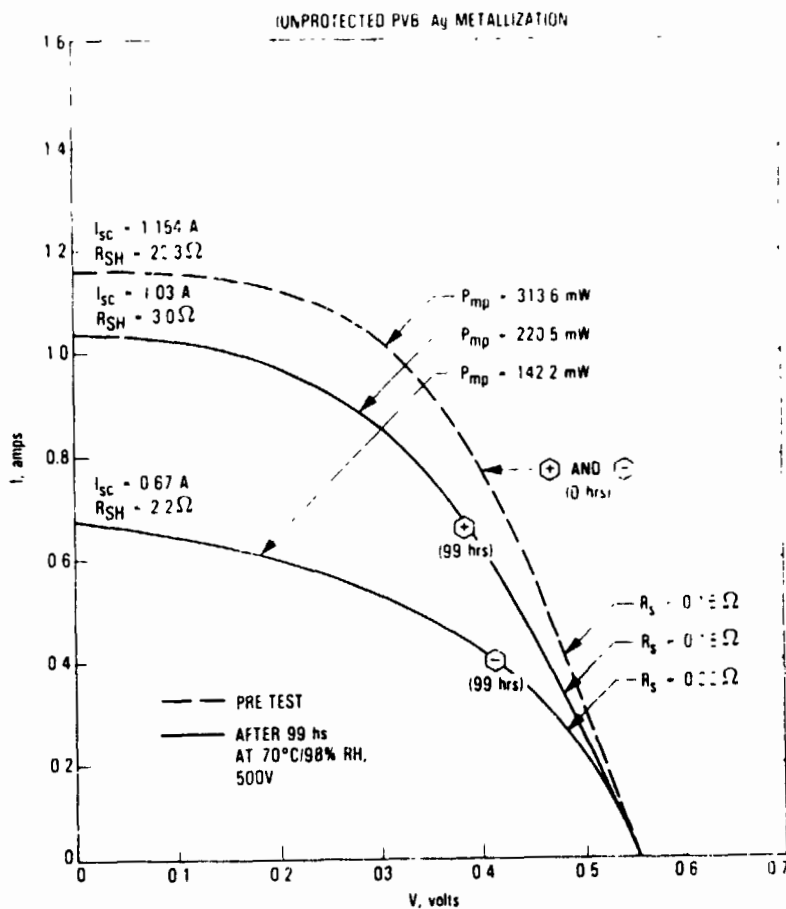
- Evolution of gas at cathode (cell) between metallization and silicon substrate -- metallization delamination
- Formation of corrosion salts at anode (frame)

#### ■ Both polarities

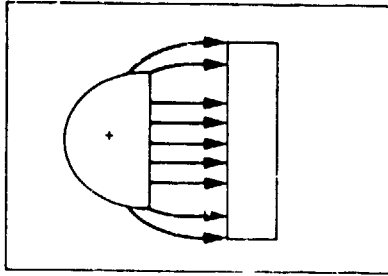
- Reduction of cell power output
- Increase in cell series resistance

# Power Reduction and Series Resistance vs Time, Showing Effects of Polarity and Non-Metallized Substrate Films

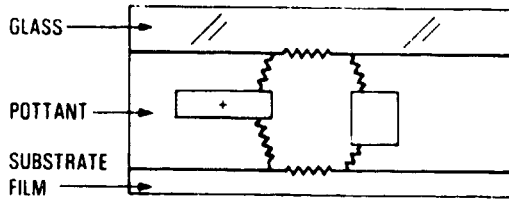


Influence of Electrochemical Damage  
on Cell I-V Performance

## Observed Current Paths

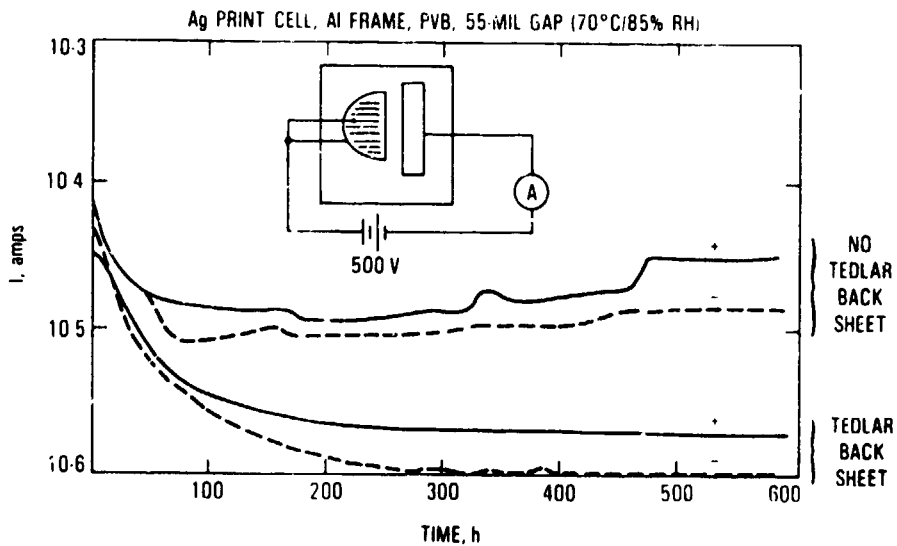


- Metallization ions follow electric field lines

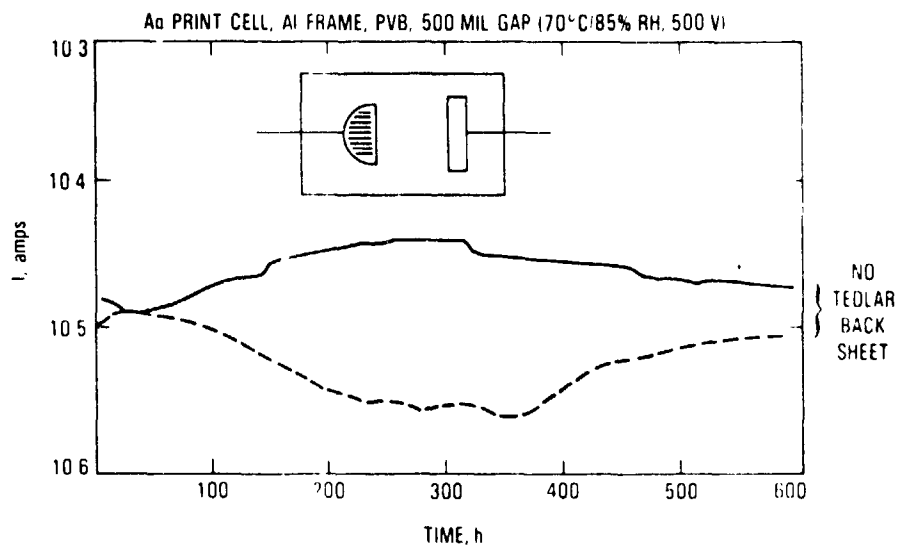


- Metallization ions often proceed to, and then along, interfacial surfaces

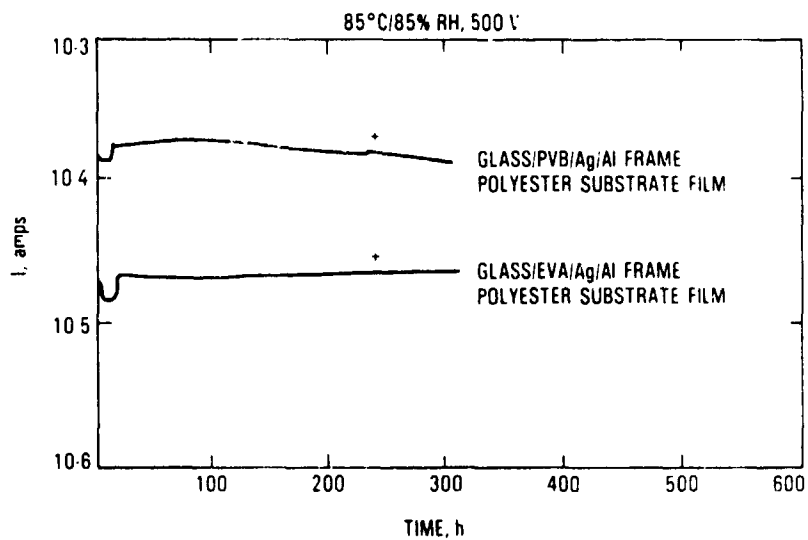
## Current Response for Small-Gap Samples and the Effect of Non-Metallized Polymer Substrate Films



## Current Response for Large-Gap Sample



## Current Response of Minimodules, Comparing PVB and EVA Encapsulants



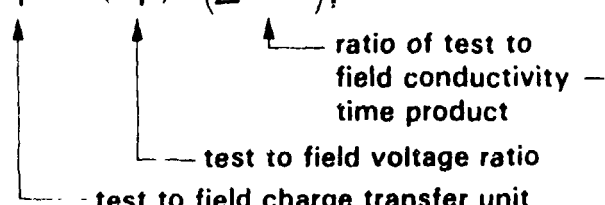
## Physical Deductions

- At large cell-frame gaps and/or low voltages, capacitive charging and polarization currents are absent because
  - Interelectrode capacitance is small
  - Electrode forces on interelectrode dipoles are weak
- Equilibrium current is independent of gap, other things being equal, because of the relatively low-resistance surface-active paths
- The magnitude of the equilibrium current is directly proportional to the pottant volume conductivity (actually, ion mobility) along paths in the bulk of the pottant
- Independent of voltage breakdown considerations, substrate polymer films provide higher surface resistance paths, hence lower equilibrium current levels

## Electrochemical Damage: Laboratory-Field Equivalence

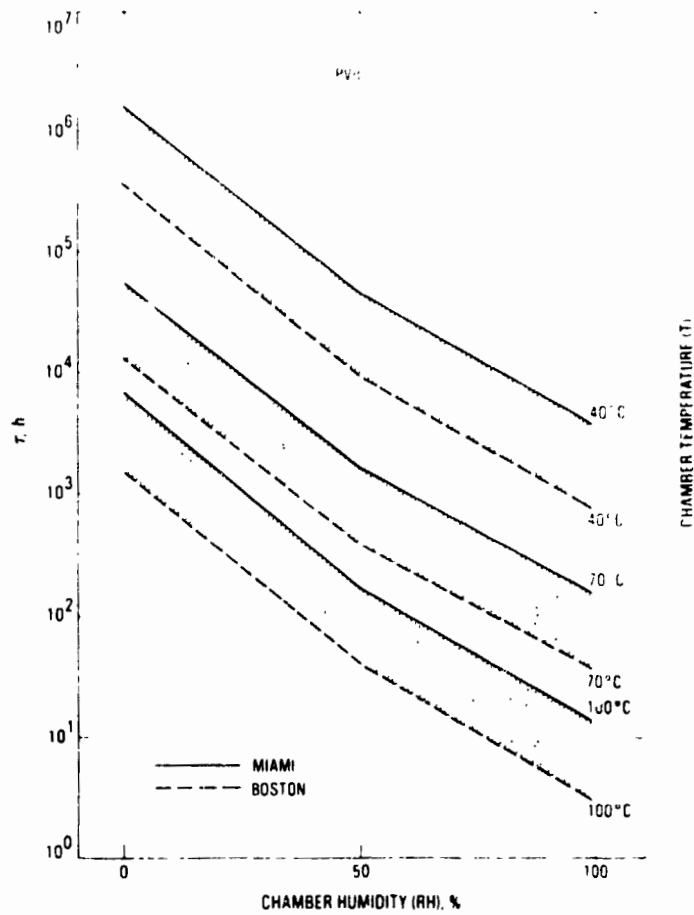
- Assumption: Equal quantities of charge transfer in the field and test environments produce equivalent amounts of electrochemical degradation
- Ohm's law:  $Q = I\tau = V \cdot (\sigma\tau) \cdot (\text{geometric terms})$
- Field time in years equivalent to  $\tau_T$  hours at test conditions:

$$Y_{EQ} = \frac{Q_T}{Q_F} = \left( \frac{V_T}{V_F} \right) \cdot \frac{(\sigma\tau)_T}{(\sum \sigma_i \tau_i)_F}$$



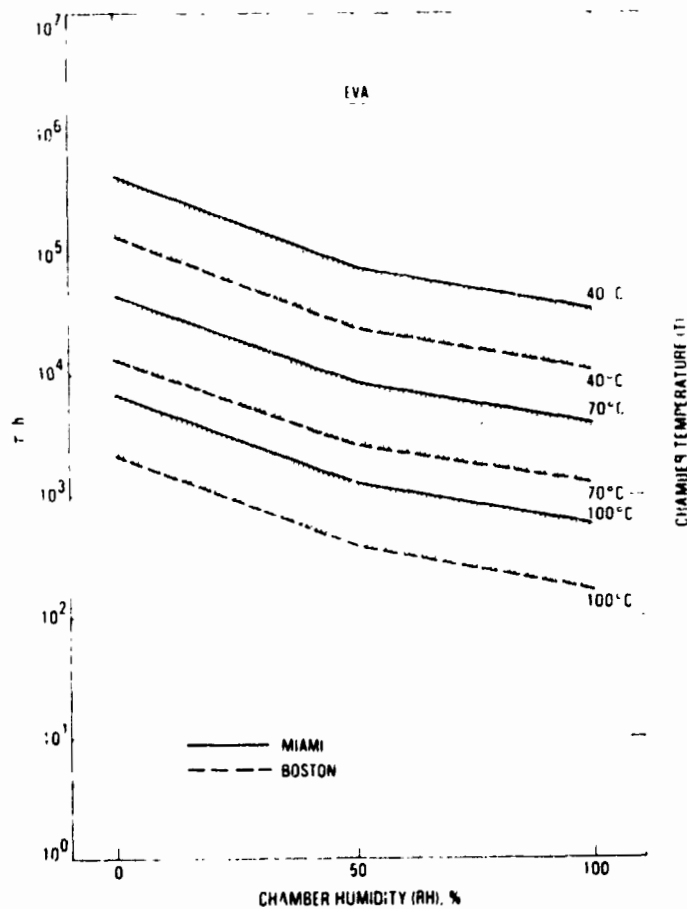
- Field values are based on yearly compilations from reduced SOLMET weather data

Test Chamber Time : Equivalent To  
30 Years In The Field





Test Chamber Time  $\tau$  Equivalent to 30 Years  
in the Field: EVA

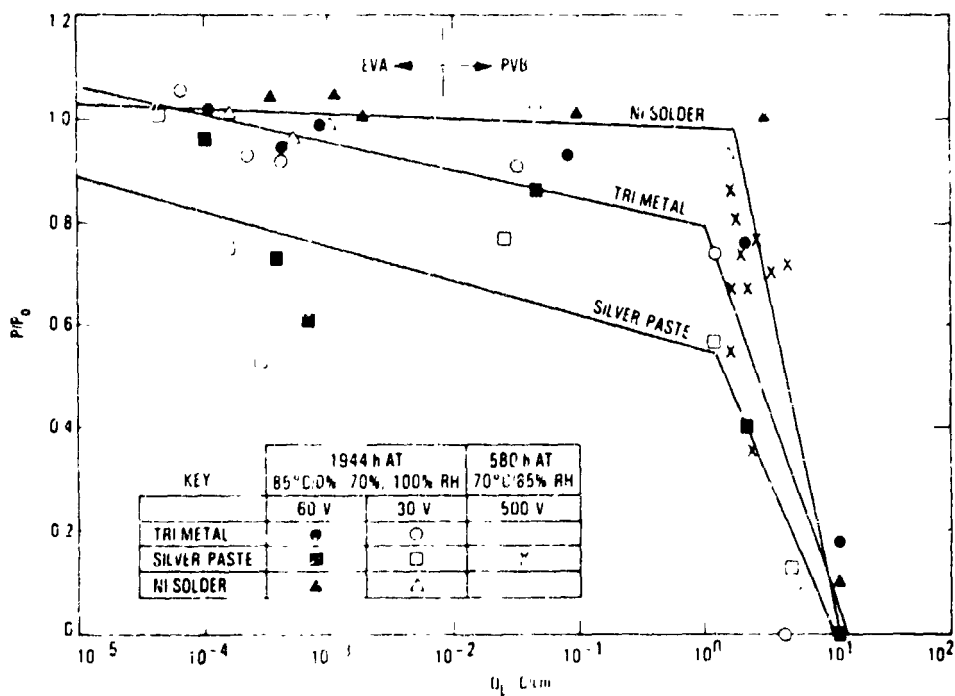


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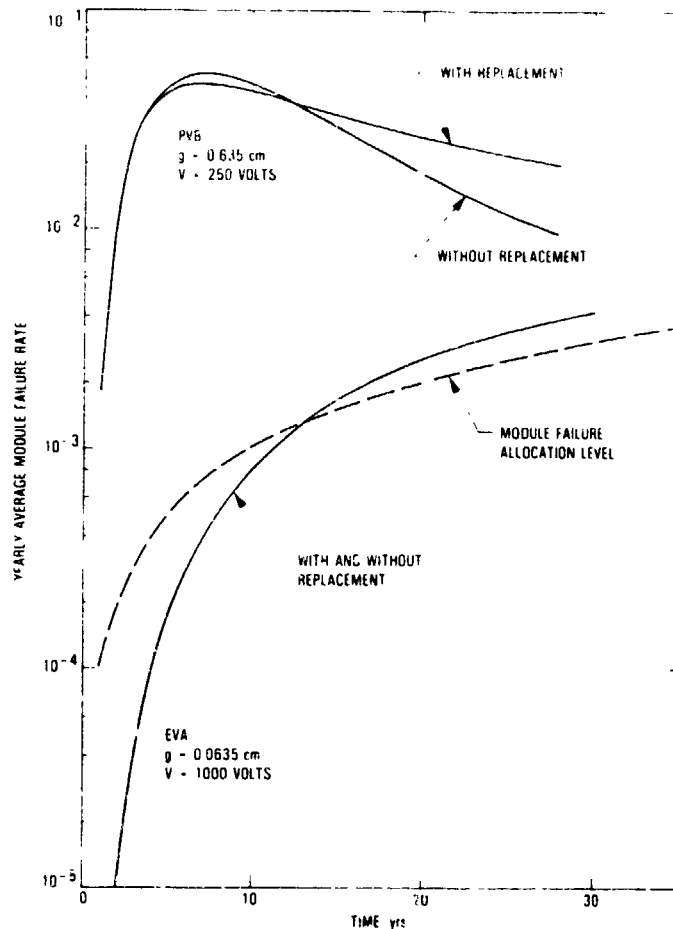
## Module Life Prediction

- Median cell failures are experimentally determined to occur with the passage of about  $Q_T = 1 - 2$  C/cm of charge between cell and frame
- Median time to cell failure is  $\tau_M = \frac{Q_T}{Q_F}$ 
  - Calculate charge transfer in the field,  $Q_F$ , using known dependencies on T and RH and SOLMET weather data
  - Assume a log-normal distribution of cell failures
- Calculate average module field failure rate
  - Without replacement (23rd PIM)
  - With replacement (this PIM)

## Power Output Reduction vs Accumulated Charge Transfer



## Module Failure Rate vs Time for 4 × 4-ft-Square-Celled Modules at Miami

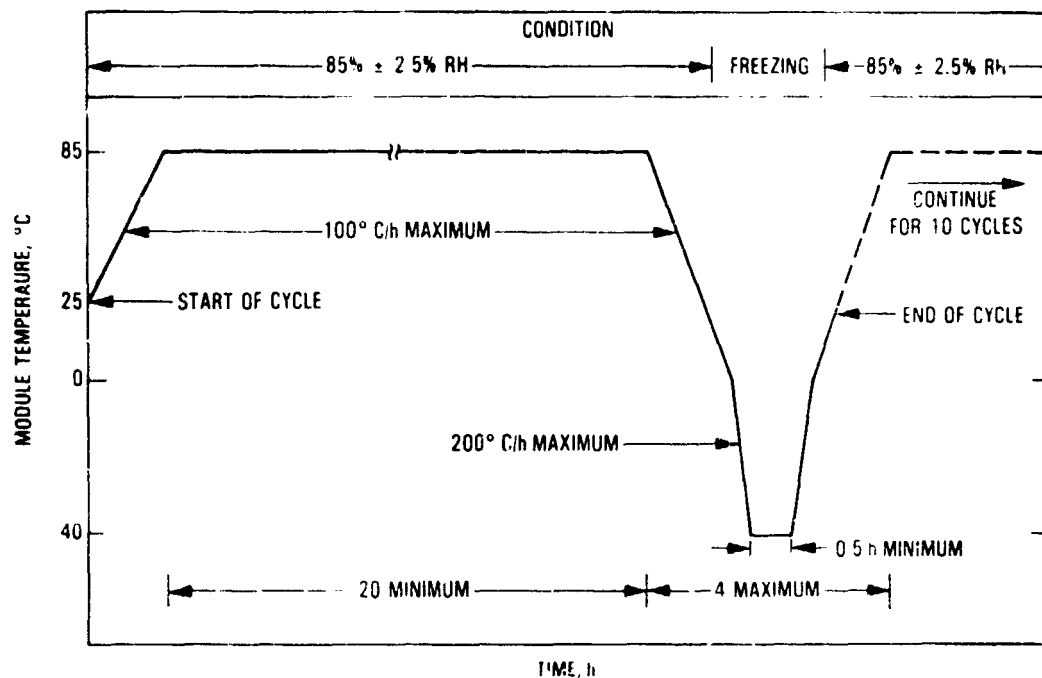


### Conclusions

- Calculated failure rates for unprotected PVB modules exceed allocation levels
- Failure rates for EVA modules fall within allocation guidelines
- Added mathematical rigor engendered by considering that replacement minimally impacts computed module failure rate results

## RELIABILITY PHYSICS

### Block V Qualification Test Temperature-Humidity Profile



### Electrochemical Qualification Test Results: 500 Vdc, 85°C/85% RH for 20 h, -40°C for 4 h, 10 24-h Cycles

Sample	Polarity	Metallization	Encapsulation	Metal Substrate Foil?	Q200, C/cm	P/P <sub>0</sub>	I/I <sub>0</sub>	Equivalent 500-V Field Exposure Miami, yr*
MO 5107	P	Pd/Ni-solder	PVB	Y	1.17	0.95	0.91	1.8
PW 5222	P	Ni-solder	PVB	Y	1.53	0.97	0.96	1.8
AS 200307	P	Print Ag	PVB	Y	3.61	0.96	0.96	1.8
AS 107461	P	Print Ag	PVB	N	2.91	0.17	0.32	84.0
MO 5117	N	Pd/Ni-solder	PVB	Y	0.737	0.79	0.97	1.8
PW 5224	N	Ni-solder	PVB	Y	0.0034	1.0	1.0	1.8
AS 200303	N	Print Ag	PVB	Y	0.181	0.99	1.01	1.8
AS 107449	N	Print Ag	PVB	N	1.41	0.88	0.94	84.0
MS 4887	P	Ni-Cu-Sn	EVA	Y	0.031	0.98	0.99	1.0
SP 58494	P	Ni-Sn	EVA	Y	0.072	0.93	0.98	1.0
SO 009	P	Print Ag	EVA	N	0.202	0.9	0.8	4.3
AS 022	P	Print Ag	EVA	N	0.534	0.96	0.97	4.3
MS 4954	N	Ni-Cu-Sn	EVA	Y	0.052	0.53	1.0	1.0
SP 58487	N	Ni-Sn	EVA	Y	0.006	1.06	0.98	1.0
SO 011	N	Print Ag	EVA	N	0.346	0.73	0.9	4.3
AS 021	N	Print Ag	EVA	N	0.205	0.94	0.96	4.3

\* Values in last column assume that foil modules are water-free (temperature acceleration only) and that non-foil modules instantly track the environmental temperature and humidity

## Conclusions

- An equivalence relationship for electrochemical degradation, based upon equal charge transfer levels, establishes a correspondence between years in the field and hours in an accelerated stress test chamber
- Adding voltage to the Block V temperature-humidity test provides an electrochemical qualification test of modules
  - Equivalent to 1 to 2 years for foil-back modules
  - Equivalent to 4 to 80 years for non-foil-back modules
  - Equivalent field years are inversely proportional to the test voltage
- Temperature acceleration ratios are similar for a wide variety of module constructions and materials (factor of 2 per 10°C)
- Humidity acceleration ratios vary considerably (40 to 1), depending upon module construction and materials

## Summary and Conclusions

- The extent of electrochemical damage is dependent on the integrated leakage current
- PV electrochemical degradation mechanisms in the two polarities are different
  - Degradation rates in the two polarities are of the same order of magnitude
  - Center-tapped grounded arrays appear to be a preferred system configuration to minimize electrochemical degradation
- There is encouraging agreement between theory and experiment in regard to leakage current response to applied voltage, gap magnitude, and encapsulant ion mobility

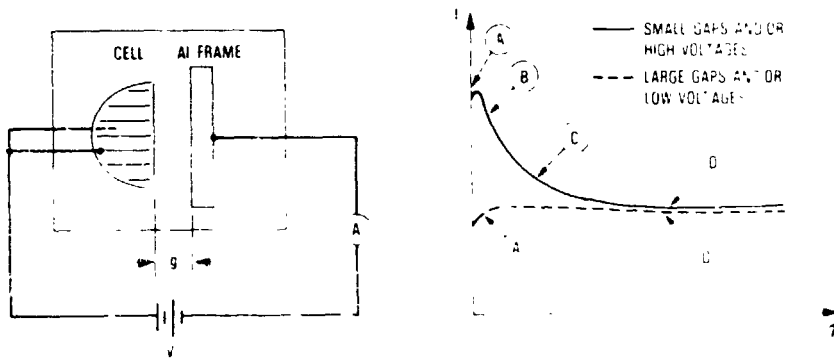
### Summary and Conclusions (Cont'd)

- Path resistance considerations suggest the use of thicker pottant layers and polymer substrate films to reduce equilibrium leakage current values
  - A metallized substrate layer, if used, should be isolated from the pottant and the frame by polyester layers
  - EVA modules appear to be consistent with 30-year-life allocation levels for electrochemical damage
- Temperature acceleration factors are well behaved and moderately well understood; humidity acceleration factors vary radically with module construction and materials and require additional research

### Additional Work Required to Finalize Understanding of Photovoltaic Electrochemical Corrosion

- Quantify temperature-humidity dependency of equilibrium leakage currents
- Quantify temperature-humidity levels of encapsulants in fielded modules

## Leakage Current Response Mechanisms



### Current response characteristics

- Ⓐ → Water absorption current (impurity ion removal)
- Ⓑ → Capacitive charging current
- Ⓒ → Polarization currents (polymer and water dipoles)
- Ⓓ → Equilibrium ion current (metallization ion diffusion)